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GIS-based optimization for advanced biofuels supply chains: a case study in Tennessee

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Abstract. Biofuel production from lignocellulosic biomass (LCB) is being advocated as an alternative to fossil-based transportation fuels in the United States. Given the substantial technical barriers related to the harvest, storage, and transportation of the LCB feedstock, this study developed a GIS-based mixed integer programming model to evaluate how the spatial and geographic attributes affect the optimal placement and configuration of a switchgrass-based biofuel supply chain. Using west Tennessee as a case study, results indicate that the type of agricultural land converted to feedstock production and the transportation cost of hauling feedstock and biofuels were influential to the selection of the most profitable supply chain configuration. The location of the conversion facilities and feedstock draw areas were also related to the choice of agricultural land use for feedstock production and the cost of hauling feedstock and advanced biofuels.

Keywords: mixed-integer programming; GIS; optimization; supply chain; biofuels; location

Introduction

Much of the focus on the development of a lignocellulosic biomass (LCB) biofuel industrial sector in the United States is on an efficient LCB feedstock supply chain. LCB produced from dedicated energy crops, agricultural residues, forest resources, and other byproducts are potentially available in abundant quantities but have a low bulk density relative to their energy content (U.S. Department of Energy, 2011). Currently, production of advanced biofuels using LCB feedstock is not cost competitive with fossil fuels and first-generation biofuels derived from crops such as corn or sugar cane. Substantial technical barriers related to the efficient harvest, storage, and transportation of low bulk density LCB feedstock impedes commercialization of advanced biofuels (U.S. Department of Energy, 2007). Given the aforementioned issues, developing an efficient supply chain that consists of the upstream (i.e. LCB production, collection, storage and transportation), midstream (biofuel conversion), and downstream (biofuel delivery to blending sites or gas pumps) activities is key for this industry to gain ground.

The design and economics of an efficient LCB biofuel supply chain has been receiving increased attention in the bioenergy literature because of the prospect of developing a LCB biofuel industry in the U.S. and other countries (Sharma *et al*., 2013). With the exception of several recent studies (e.g. Chen and Fan, 2012; Marvin *et al*., 2013), most of the existing studies have only evaluated upstream activities within a supply chain for biofuels (An *et al*., 2011). In addition, most studies have ignored the spatial and geographic attributes of a region that are related to the optimal placement and configuration of a supply chain (Noon *et al*. 2002). Regional attributes that may affect the optimal configuration of the supply chain include: 1) available land resources for growing feedstock in relation to the biofuel end-user market, 2) the real road network for movement of feedstock and biofuel products, 3) available infrastructure for placement of the conversion facility, and 4) the opportunity costs of converting agricultural land to LCB production are potentially important factors (Archer and Johnson, 2012).

This study applies a geographical information system (GIS)-based mixed integer programming model to evaluate how the spatial and geographic attributes of a region affect the optimal placement and configuration of a switchgrass-based biofuel supply chain. The analysis is applied to a case study in Tennessee where plant-gate costs of switchgrass may be influenced by the geographically dispersed and relatively complex landscapes upon which agricultural crops are grown in Tennessee, when compared to other regions such as the mid-continental U.S.

Analytical model

A mixed-integer mathematical programming model integrating high resolution agricultural land and local infrastructure data was developed to evaluate the impact of spatial attributes on the configuration of an advanced biofuel supply chain. The biofuel supply chain included biomass feedstock establishment and production in the field, feedstock collection and delivery to conversion facilities, biofuel and co-product conversion, and shipment of biofuel to blending facilities. The location of conversion facilities and the configuration of feedstock draw areas were determined by maximizing net present value of cash flows (NPV) within biofuel supply chains. The software used to solve this model is General Algebraic Modeling System (GAMS) version 24.2 using the CPLEX solver.

The NPV objective in equation (1) includes investment in year 0 in conversion facilities (INV^{fac}) establishment cost of switchgrass feedstock (EST^{swi}) in year 0 and the discounted salvage value of the conversion facilities ($SALV^{fac}$) in year T using discounting factor $\theta_t = (1+r)^{-T}$ where *r* is the discount rate. Discounted annual net cash flows in time *t* using θ_t from supply chain activities were derived by subtracting annual sales of advanced biofuel (R_t^{bio}) and co-products (R_t^{co}) from the costs of switchgrass production (C_{ft}^{swi}), feedstock storage (C_{st}^{swi}), feedstock transportation (C_{ht}^{swi}), biofuel conversion (C_{ot}^{bio}) and biofuel transportation (C_{ht}^{bio}). The calculation of each component is presented in equation (1) and the definitions of the variables and parameters used in the model are in Table 1. Given that a market for switchgrass has not been established in Tennessee, the price used to calculate the production cost (C_{ft}^{swi}) of switchgrass is the breakeven price (BEP) presented in equation (2). The breakeven price of switchgrass needs to be at least cover the profits of current cropping activities $\left(Price_{ip} \times Yield_{ip} - PC_{ip}\right)$, i.e. the opportunity cost of land conversion and the production cost of feedstock. Land rent (LR) was considered as opportunity cost for land conversion if the profits of the current cropping activity were less than the market rent.

Table 1. Definition of Variables and Parameters for the Mixed-Integer Programming Model

Variables/ Parameters/ Subscripts	*Unit*	*Definition*
A	*ha*	hectares (ha) of switchgrass produced annually
AH	*ha*	switchgrass harvested monthly from November through February
Bio		binary variable; 1 if the industrial park is selected to locate conversion facility, 0 if not.
NXS	*Mg*	tons of switchgrass newly stored monthly from November to February
Numb		number of equipment used in harvest
XC	*Mg*	switchgrass produced annually
XH	*Mg*	switchgrass harvested monthly from November through February
XQ	*Kl*	kiloliter (Kl) of advanced biofuel produced in each month
XQC	*Kl*	quantity of co-product produced in each month
XS	*Mg*	switchgrass stored monthly from November through October
XTN	*Mg*	switchgrass transported directly to the conversion facility during harvest period
XTO	*Mg*	switchgrass transported from storage to the conversion facility during off-harvest period
Parameters		
β	*\$/plant*	investment cost of conversion facilities
α	*\$/ha*	establishment cost of switchgrass
θ	*%*	discount factor
δ		salvage factor
γ	*\$/ton*	storage cost per ton
τ	*\$/ton*	transportation cost per ton from field to the conversion facility
P	*\$/Kl*	biofuel conversion cost
Ω	*\$/Kl*	Biofuel transportation cost

Variables/ Parameters/ Subscripts	*Unit*	*Definition*
Λ	*Kl/Mg*	conversion rate of switchgrass to advanced biofuel
Aa	*Ha*	cropland available in each hexagon for each crop
AM	*$/ha*	annual maintenance cost for switchgrass
Avehour	*Hour*	available average harvest hours based on weather in each month
BEP	*$/ha*	breakeven price of planting switchgrass as alternative to current crop production
Cap	*Kl*	nameplate capacity of conversion facility
D	*Kl*	monthly demand of biofuels at the blending sites
$DMLS$	*%*	dry matter loss during storage
$DMLT$	*%*	dry matter loss during transportation
MT	*hour/ha*	machine time per ha for each machinery
PAS	*%*	ratio of agricultural land to be converted for switchgrass
Sigma	*$/ha*	annual harvest cost for switchgrass
$yield^{swi}$	*Mg/ha*	switchgrass yield
Subscripts		
b		harvest method (rectangular baler, round baler)
g		conversion facility capacity
i		locations of switchgrass production field
j		locations of the conversion facilities
k		locations of the blending sites
m		month
p		type of cropland
t		Year

Equations (3)-(13) summarize the constraints in the model. Equations (3) and (4) limit feedstock production in each spatial unit to the available agricultural land and the switchgrass production on that land. Equation (5) indicates that switchgrass was harvested from November through February. The amount of switchgrass harvested each month is constrained by available harvest hours based on weather in each month ($rate_m$) in equation (6). Equation (7) assures that enough machinery was available for switchgrass harvest. Equation (8) constrains feedstock delivery to not be more than the harvest, while equation (9) limits monthly delivery of feedstock to not exceed current inventory. Equation (10) constrains switchgrass inventory to equal the amount stored in the previous month in addition to the newly stored amount during the harvest period. During the off-harvest period, equation (11) assures that switchgrass inventory equaled the amount stored in the current month less the amount of switchgrass delivered to the facility in the following month. Equation (12) indicates that switchgrass delivered to the facility each month meets the demand of all conversion facilities, and equation (13) constrains monthly demand of biofuels by blending facilities to the amount of biofuel production provided by the conversion facilities.

$$\text{Max.}\quad NPV = -INV^{fac} - EST^{swi} + \theta_T(SALV^{fac}) + \sum_t \theta_t[(R_t^{bio} + R_t^{co}) - C_{ft}^{swi} - C_{st}^{swi} - C_{ht}^{swi} - C_{ot}^{bio} - C_{ht}^{bio}]$$

$$= -\Big((\sum_j \sum_g \beta_g \times Bio_{jg}^{fac}) + (\sum_i \sum_p \frac{\alpha}{Yield_i^{swi}} \times XC_{ip}^{swi})\Big) + \theta_T(\sum_j \sum_g \delta_g \times Bio_{jg}^{ref})$$

$$+ \sum_t \theta_t[(\sum_j \sum_g \sum_m Pr^{bio} \times XQ_{jgm} \times Bio_{jg}^{fac}) + (\sum_j \sum_g \sum_m Pr^{co} \times XQC_{jgm} \times Biojgfac$$

$$-(\sum_i \sum_p \sum_b \mathrm{BEP_{ipb}} \times \mathrm{XC_{ipb}}) + (\sum_m \sum_p \sum_i \sum_b \gamma_{ib} \times \mathrm{NXS_{mpib}})$$

$$- \sum_i \sum_j \sum_b \tau_{ijb} \times \frac{(\sum_m \sum_p \mathrm{XTN_{mpib}} + \sum_m \sum_p \mathrm{XTO_{mpib}})}{1-\mathrm{DML_{trans}}}$$

$$-(\sum_g \sum_j \rho \times XQ_{jgm}) + \sum_j \sum_k(\omega_{jk} \times XQ_{jm})] \qquad (1)$$

$$\mathrm{BEP}_{ipb} = \begin{cases} \frac{(Price_{ip} \times Yield_{ip} - PC_{ip}) + AM + \mathrm{Sigma}_{ib}}{Yield_i^{swi}}, & \text{if } (Price_{ip} \times Yield_{ip} - PC_{ip}) \geq LR_{ip} \\ \frac{LR_{ic} + AM + \mathrm{Sigma}_{ib}}{Yield_i^{swi}}, & \text{if } (Price_{ip} \times Yield_{ip} - PC_{ip}) < LR_{ip} \end{cases} \qquad (2)$$

Subject to:

$$\mathrm{A}_{ip} \leq PAS_p \times aa_{ip}, \ \forall i, p \qquad (3)$$

$$XC_{\mathrm{ipb}} \leq \mathrm{yield}_{ipb}^{sw} \times A_{\mathrm{ipb}}, \ \forall \mathrm{i, p, b} \qquad (4)$$

$$XH_{\mathrm{mipb}} = 0, \ \mathrm{March} \leq \mathrm{m} \leq \mathrm{Oct}\ \forall \mathrm{m, i, p, b} \qquad (5)$$

$$\sum_{ipb} XH_{mipb} = \frac{\mathrm{Cap}}{\lambda} \times rate_m, \ \mathrm{m = Nov, Dec, Jan}\ \&\ Feb \qquad (6)$$

$$Numb_{\mathrm{mb}} \times avehour_{\mathrm{m}} - \sum_i \sum_p (MT_{\mathrm{ib}} \times AH_{\mathrm{mipb}}) \geq 0, \ \forall \mathrm{m, b} \qquad (7)$$

$$XH_{\mathrm{mipb}} - \frac{\sum_j XTN_{\mathrm{mipb}}}{1-\mathrm{DMLT}} \geq 0, \ \forall \mathrm{m, i, p, b} \qquad (8)$$

$$XS_{\mathrm{mipb}} - \frac{XTO_{\mathrm{(m+1)ipb}}}{1-\mathrm{DMLT}} \geq 0, \ \forall \mathrm{m, i, p, b,} \qquad (9)$$

$$XS_{mipb} = (1 - \mathrm{DMLS}_{(m-1)ib}) \times XS_{mibp} + NXS_{mibp}, \quad Nov \leq m \leq Feb\ \&\ \forall m, i, p, b \qquad (10)$$

$$XS_{(m+1)ipb} = (1 - DMLS_{mib}) \times XS_{mipb} - \frac{XTO_{(m+1)ipb}}{1-DMLT}, \quad March \leq m \leq Oct\ \ \forall m, i, p, b \qquad (11)$$

$$\lambda \sum_j [(\sum_i \sum_p \sum_b XTN_{\mathrm{mipbj}} + \sum_i \sum_p \sum_b \sum_t XTO_{\mathrm{mipbj}}) - \mathrm{XQ}_{mj}] \geq 0, \ \forall \mathrm{m, j} \qquad (12)$$

$$\sum_j XQ_{jm} = D_m, \ \forall \mathrm{m} \qquad (13)$$

Case Study and Data

West Tennessee was selected as the case study area because it is the largest agricultural production area in the state. Also, the biggest city in the state, Memphis, is located in the region and has a high demand for transportation fuel. In 2011, about 11.7 million kiloliters (Kl) of gasoline were used in the state. Assuming that the state's goal is to replace 20% of gasoline use with biofuels and half was produced in the west Tennessee, the annual demand in the region would be about 1.14 million Kl. The biofuel price including the cost of the Renewable Identification Number was projected at $1,138.58 per Kl at the blending sites (Donahue *et al*., 2010). Two nameplate capacities of conversion facility, 0.38 million Kl per year (Kly) and 0.19 million Kly, were considered in the analysis based on an industrial expert's opinion. The facility was assumed to be located in an industrial park in the region to access required infrastructure such as power lines, roads, and water system. Switchgrass was assumed to be the feedstock grown on agricultural lands converted from its current use in crops, hay and pasture. The profitability of hay and pasture is generally low when compared to cash crops such as corn and cotton. Thus, the opportunity cost of converting hay and pasture land to switchgrass is typically less when compared with other crops. Hay and pasture land is also the feedstock source for local cattle industry. Thus, the availability of low opportunity cost land for switchgrass was also considered in the analysis. The three scenarios for the amount of hay and pasture land converted to switchgrass production that were evaluated in this study were: (a) no limit on the amount of hay and pasture land converted, (b) an upper limit of 50% on hay and pasture land converted and (c) an upper limit of 25% of hay and pasture land converted. Feedstock was harvested annually from November to February under available working hours in each month that was estimated based on historical weather records. Switchgrass was harvested using large rectangular bales that were stored at the edge of the field and the cost of storage dry matter losses were considered in the model (Mooney *et al*., 2012).

Land area in the region was decomposed into land resource units consisting of five square-mile hexagons. For each land resource unit, prices, yields and areas of different crops available for conversion to switchgrass production were obtained from the U.S. Department of Agriculture. Simulated yields of switchgrass were from Jager *et al*. (2010). County level yields for the existing crops and switchgrass were disaggregated to the land resource unit based on an index of soil quality. In addition, the street level network from the U.S. Census of Bureau was overlaid on the land resource units to generate transportation routes for moving feedstock to conversion facilities and moving biofuel to blending stations. Equipment operating and capital costs were calculated following procedures from the American Society of Biological and Agricultural Engineers the Agricultural and Applied Economics Association.

Results

Table 2 summarizes the revenues, costs, NPV of cash flows, and land use changes in the biofuel supply chain under different hay and pasture land conversion scenarios. To supply 1.14 million Kly of biofuel to replace 20% of liquid transportation fuel consumption, a total four 0.38 million Kly conversion facilities with a capacity factor of 80 percent were selected given the size economies in biofuel production. Given a fixed annual demand for biofuel, the annual revenue stream is the same over all three available hay and pasture land scenarios. With a projected price of $1,138.58 per Kl, the four conversion facilities in aggregate will have an annual revenue stream of $1.328 billion including the value of the electricity co-product. Every $1 decrease in the biofuel price lowered the annual revenue stream by 25%.

Table 2. NPV of profit, and land use changes in the biofuel supply chain

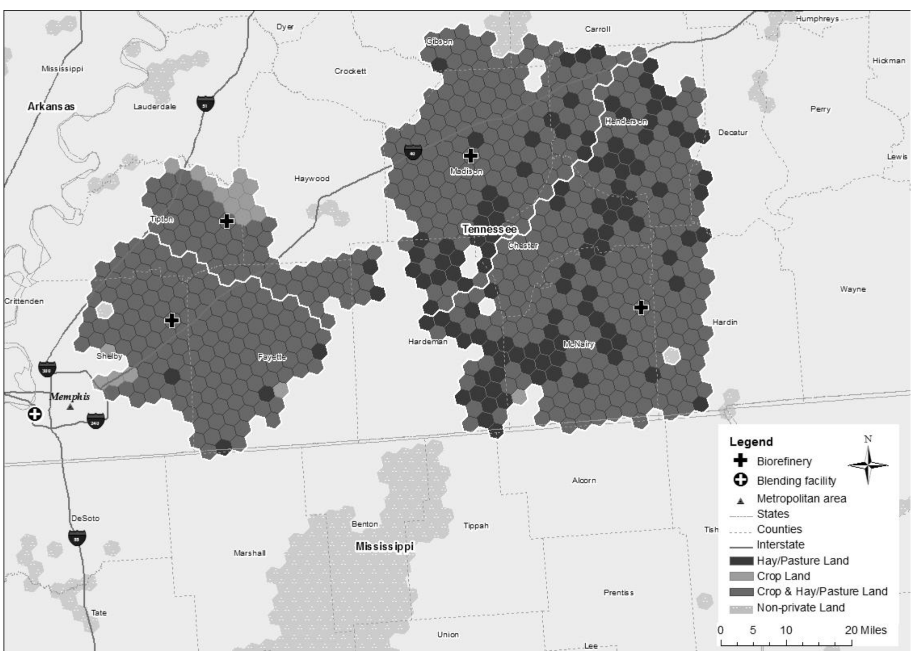
		Hay and pasture constraint scenarios		
	Unit	(a)	(b)	(c)
annual sales revenue from ethanol	million $	1,293.00	1,293.00	1,293.00
annual byproducts from biorefinery	million $	35.48	35.48	35.48
total annual revenue	million $	*1,328.48*	*1,328.48*	*1,328.48*
	million $			
annual switchgrass opportunity costs	million $	38.25	40.13	40.46
annual switchgrass maintainence cost	million $	21.71	21.85	21.85
annual switchgrass harvest and operation costs	million $	129.06	129.49	129.48
annual switchgrass storage cost	million $	15.23	15.23	15.23
annual switchgrass transportation cost	million $	50.09	52.79	53.06
annual biofuel transportation cost	million $	7.96	5.03	5.03
annual biorefinery operation costs	million $	384.35	384.35	384.35
total annual cost	million $	*646.65*	*648.88*	*649.46*
switchgrass establishment cost at year 0	million $	28.30	28.49	28.49
biorefinery investment cost at year 0	million $	3,151.36	3,151.36	3,151.36
biorefinery salvage at year 10	million $	326.14	326.14	326.14
NPV of proift over 10 years	million $	*2,879.16*	*2,859.98*	*2,855.00*
Total harvest area	*1,000 hectares*	*187.61*	*188.85*	*188.82*
total cotton acreage	1,000 hectares	65.81	84.15	89.48
total sorghum acreage	1,000 hectares	1.46	2.09	2.10
total soybeans acreage	1,000 hectares	71.30	74.05	76.76
total wheat acreage	1,000 hectares	10.52	12.09	12.26
total hay & pasture acreage	1,000 hectares	38.52	16.47	8.23

Scenario (a): no contraint on hay & pasture land; Scenario (b): maximum of 50% of hay & pasture lands converted; Scenario (c): maximum of 25% of hay & pasture lands converted.

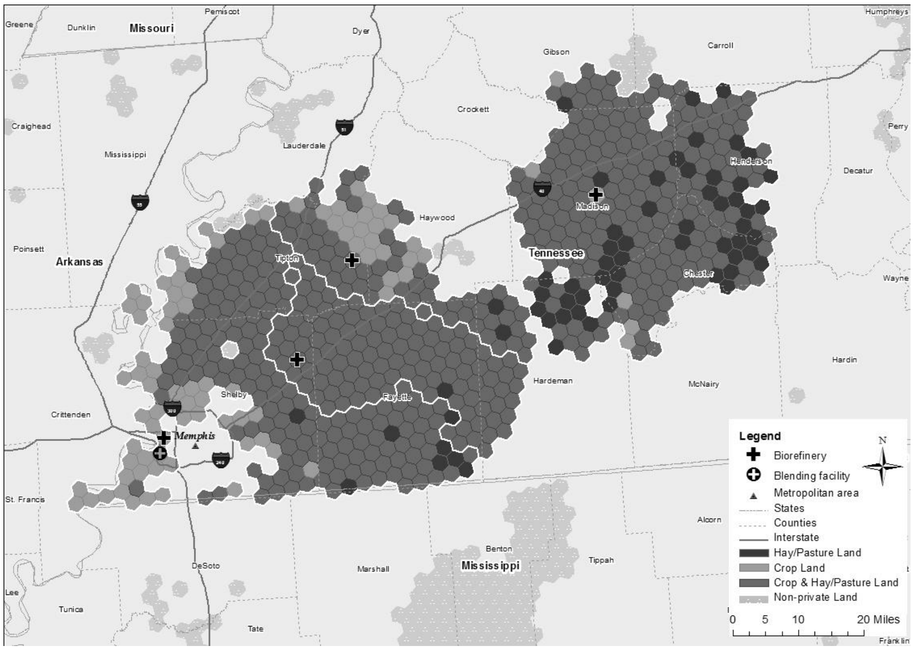
The costs of operation differed among the three hay and pasture land scenarios. Annual opportunity costs defined as the profit from the previous land use prior to conversion was the lowest for the no constraint on hay and pasture conversion scenario [Scenario (a)] at $38.25 million. When imposing constraints on the amount of land conversion from hay and pasture lands, opportunity costs increased to over $40 million for the 50% [Scenario (b)] and 25% [Scenario (c)] limits on the conversion of hay and pasture lands. Feedstock transportation costs also differed among the three hay and pasture conversion scenarios. The cost of hauling feedstock to the conversion facilities was about $50 million when there was no constraint on the amount of hay and pasture lands converted. For Scenarios (b) and (c), transportation costs increased to $52.8 and $53.1 million, respectively, given the longer distance to land with lower opportunity cost for feedstock. However, because Scenarios (b) and (c) located the conversion facilities closer to Memphis (see Figure 1), biofuel transportation costs decreased relative to the no limit on the conversion of hay and pasture land scenario by about $3 million ($5.03 million vs. $7.98 million). Annual switchgrass maintenance costs increased slightly in Scenarios (b) and (c) resulting from the 1,240 additional switchgrass hectares (ha) required by the conversion facilities.

As the amount of pasture and hay converted to feedstock production in the supply region increased, the NPV of profits for the supply chain increased. For Scenario (a), NPV over 10 years was estimated to be $2.879 billion. The additional opportunity cost in Scenarios (a) and (b) lowered NPV to $2.859 and $2.855 billion, respectively.

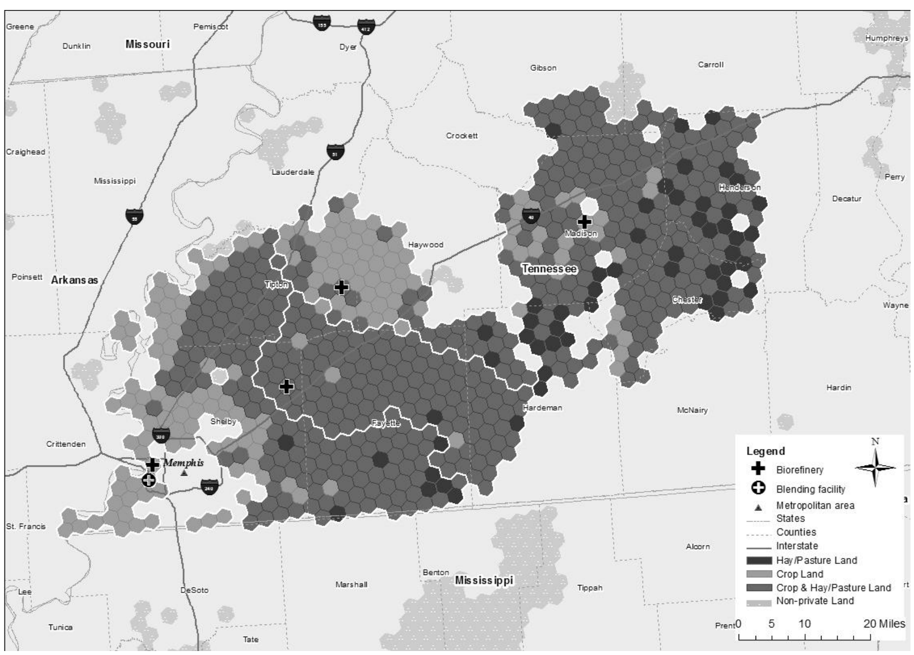
When no constraint was placed on the amount of hay and pasture land to be converted, the production of the feedstock was primarily located on the east side of the region in Figure 1(a). About 187,600 ha of switchgrass were required to create the 1.14 million Kly of biofuel. West Tennessee agriculture is dominated by the production of row and solid planted crops including corn, cotton, sorghum, soybeans, and wheat. The majority of the converted agricultural land was from soybean (38%), cotton (35%) and hay and pastures (20%). As the constraint of 50% (Scenario (b)] and 25% [Scenario (c)] of total hay and pasture land existing in the land resource units were imposed for switchgrass production, the location of one conversion facility on the southeast corner shifted towards Memphis [see Figures 1(b) and 1(c)] and the amount of land required increased to almost 188,850 ha. Cotton became the major cropland converted to switchgrass when not enough low cost hay and pasture land were available.



(**a**) No constraint on hay & pasture land



(**b**) max. 50% of hay & pasture lands converted



(**c**) max. 25% of hay & pasture lands converted

Fig. 1. The location of conversion facilities and feedstock draw areas under alternative hay and pasture land availability scenarios

Conclusions

Determining the optimal configuration of an advanced biofuel supply chain has emerged as an important reseach topic given the push to commercialize a biofuel industry in the United States. Previous studies in this area have used either a GIS model for location analyses without optimization in the decision process, or a mathematical programming model for system optimization without considering the geographic attributes of a region that affect optimal placement and configuration of a supply chain. A mixed-integer programming model linked with high resolution spatial data was developed to evaluate how the geographic attributes affect the optimal placement and configuration of an advanced biofuel supply chain. For a case study using switchgrass as a feedstock in west Tennessee, results indicated that the type of agricultural land converted to biomass feedstock production and the cost of hauling feedstock and biofuel products were influential in the selection of the most profitable biofuel supply chain configuration. The spatial concentration of lower cost agricultural land to be converted to feedstock production had an important impact on the total profit. The location of the conversion facilities and feedstock draw areas were also affected by the spatial concentration of lower cost agricultural land and the available transportation network and other infrastructure. The aformentioned spatial factors affected feedstock costs and transportation costs of feedstock and biofuel movement within the supply chain. The modeling framework developed in this study can be extended to evaluate biofuel production in other regions of the state of Tennessee and the southeastern United States for the emerging advanced biofuel industry.

References

An, H., W.E. Wilhelm and S.W. Searcy. (2011). Biofuel and petroleum-based fuel supply chain research: A literature review. Biomass and Bioenergy 35: 3763-3774.

Archer, D.W. and J.M. Johnson. (2012). Evaluating local crop residue biomass supply: economic and environmental impacts. BioEnergy Research 5: 699–712

Chen, C. and Y. Fan. (2012). Bioethanol supply chain system planning under supply and demand uncertainties. Transportation Research Part E 48: 150-164

Donahue, D. J., S. Meyer, and W. Thompson. (2010). RIN risks: using supply and demand behavior to assess risk in the markets for Renewable Identification Numbers used for Renewable Fuel Standard compliance. Proceedings of the NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management. St. Louis, MO.

Jager, H.I., L.M. Baskaran, C.C. Brandt, E.B. Davis, C.A. Gunderson, and S.D. Wullschleger. (2010). Empirical geographic modeling of switchgrass yields in the United States. GCB Bio-energy 2: 248–57

Marvin, W.A., L.D. Schmidt, and P. Daoutidis. (2013). Biorefinery location and technology selection through supply chain organization. Industrial & Engineering Chemistry Research 52: 3192-3208

Mooney, D.F., J.A. Larson, B.C. English, and D.D. Tyler. (2012). Effect of dry matter loss on profitability of outdoor storage of switchgrass. Biomass and Bioenergy 44: 33-41.

Noon, C., F.B. Zhan, and R.L. Graham. (2002). GIS-based analysis of marginal price variation with an application in the identification of candidate ethanol conversion plant locations. Networks and Spatial Economics 2: 79–93.

Sharma, B., R. Ingalls, C. Jones, and A. Khanchi. (2013). Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future. Renewable and Sustainable Energy Reviews 24: 608-627.

U.S. Department of Energy. (2007). Roadmap for Bioenergy and Biobased Products in the United States, Report of the Biomass Research and Development Technical Advisory Committee. U.S. Department of Energy, Biomass Research and Development Initiative. Washington, DC.

U.S. Department of Energy. (2011). U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. ORNL/TM-2011/224. Oak Ridge National Laboratory. Oak Ridge, TN.